LOW-POWER MILLIMETER-WAVE RADAR OBSERVATIONS OF THE ATMOSPHERE

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Introduction

Historically, cloud structures, dynamics, and precipitation processes have been observed and measured with sensors from two different spatial resolutions. Laser-based sensors have volume resolutions on the order of 10^{-4} to 10^{-2} cubic meters for a 1-s sample. Radar systems operating at wavelengths between 1 and 10 cm have resolutions on the order of 10^4 to 10^7 cubic meters. The resolutions of micro-wave systems depend primarily on the system RF bandwidth and antenna bandwidth. Both resolution regimes have been useful in the study of cloud structures and processes—the former for determining resolution on the individual cloud particle scale and the latter for studying the coarse characteristics of cloud dynamics and structure.

There are, however, cloud processes and structures that occur on scales that lie between these two regimes: the process of entrainment, where outside air is brought within the cloud boundaries; the mixing of in-cloud particles with different histories; cloud particle coalescence; and ice formation.

The use of mm-wave (30- to 300-GHz) radars offers an opportunity to observe cloud processes at these scales and determine their influence on precipitation development, cloud albedos, cloud lifetimes, chemical cycling of tract substances, aircraft icing, and other meteorological phenomena.

To determine the usefulness of a 35-GHz radar for observing these precipitation and cloud precesses, we initiated a research program. The objectives of this program are (1) to develop a 35-GHz radar, (2) to measure scattering from precipitation and clouds, and (3) to develop a model to compute scattering from clouds using the finite-difference time-domain (FDTD) technique.

Status

We developed a millimeter-wave radar at 35 GHz with a range resolution from 80 meters to less than 3 meters and a beamwidth of 2°. This yields volumetric resolutions between 10 and 10^4 cubic meters. This resolution level is needed to study spatial variations within clouds and precipitation. The modes of operation of our radar are rectangular pulse, chirped pulse, and FM-CW. The primary mission of the system is ground-based cloud and rain probing. This radar can, however, be modified for airborne applications.

Pulse mode

Figure 1 shows the block diagram of the radar in pulse mode. The radar modulation is generated at VHF and then unconverted to Ka band via C band before being applied to the Traveling-Wave Tube Amplifier (TWTA). The radar transmits a vertically polarized signal with a 30.5-cm parabolic dish. We utilized a 30.5-cm dual-polarized horn-lens antenna for reception. We used an orthomode coupler to separate the vertical and horizontal components of the scattered signal. These are downconverted, amplified and supplied to synchronous In-phase and Quadrature detectors. After video amplification and filtering, the four signal lines (vertical I, vertical Q, horizontal I, horizontal Q) are routed to the digitizer section.

The digitizer is a two-channel 100 MSPS IBM PC-based system. To handle the four video output channels, the four signals are multiplexed to the two channels of digitization. Changing from vertical to horizontal measurements is performed by software with a delay of about 300 μs. Each channel has 64K of high speed RAM to store the 8-bit data. This RAM space can be configured to store data from between 4 and 64K range cells and from 1 to 16K pulses, provided the 64K limit is not exceeded. The data are off-loaded from the A/D boards and stored on 22-MB replaceable media disks. The digitizer host PC also acts as the radar controller.

The radar is controlled by a program written in C running on the IBM PCAT host. With each data file, the program stores the radar control status as well as telemetry from the radar. The telemetry consists of the elevation pointing angle, radar bus voltages, and temperatures at five locations in the system. This telemetry is ported to the PC through an RS-232 data link. The monitor and keyboard of the PC act as the user interface and can be located up to 40m from the radar. They are connected to the radar via a shielded parallel data link.

The radar is capable of two types of pulse modulation. A 1-μs rectangular pulse is used for coarse resolution probing and a 15-ns chirped pulse is used for high resolution measurements. The pulses are generated with integrated lumped-constant delay lines modulating a 240-MHz carrier via a GaAs FET switch. The switch insures a pulse rise time of less than 3 ns. In the 15-ns mode, the pulse is passed through a dispersive filter with a time-bandwidth-product (TBP) of 80 for an effective signal gain of 18 dB over a non-chirped 15-ns pulse. Table 1 summarizes the specifications of the radar in pulse mode.

Table 1. Specifications of Radar in Pulse Mode

Pulse Width	15ns chirped, 1 μs rectangular
Range Resolution	3 meters, 150 meters
Pulse Repetition Frequency	95 to 8,138 Hz
High Speed Memory	128K (2 channels @ 64K 100 MSPS)
Data Products	Amplitude and Doppler velocity

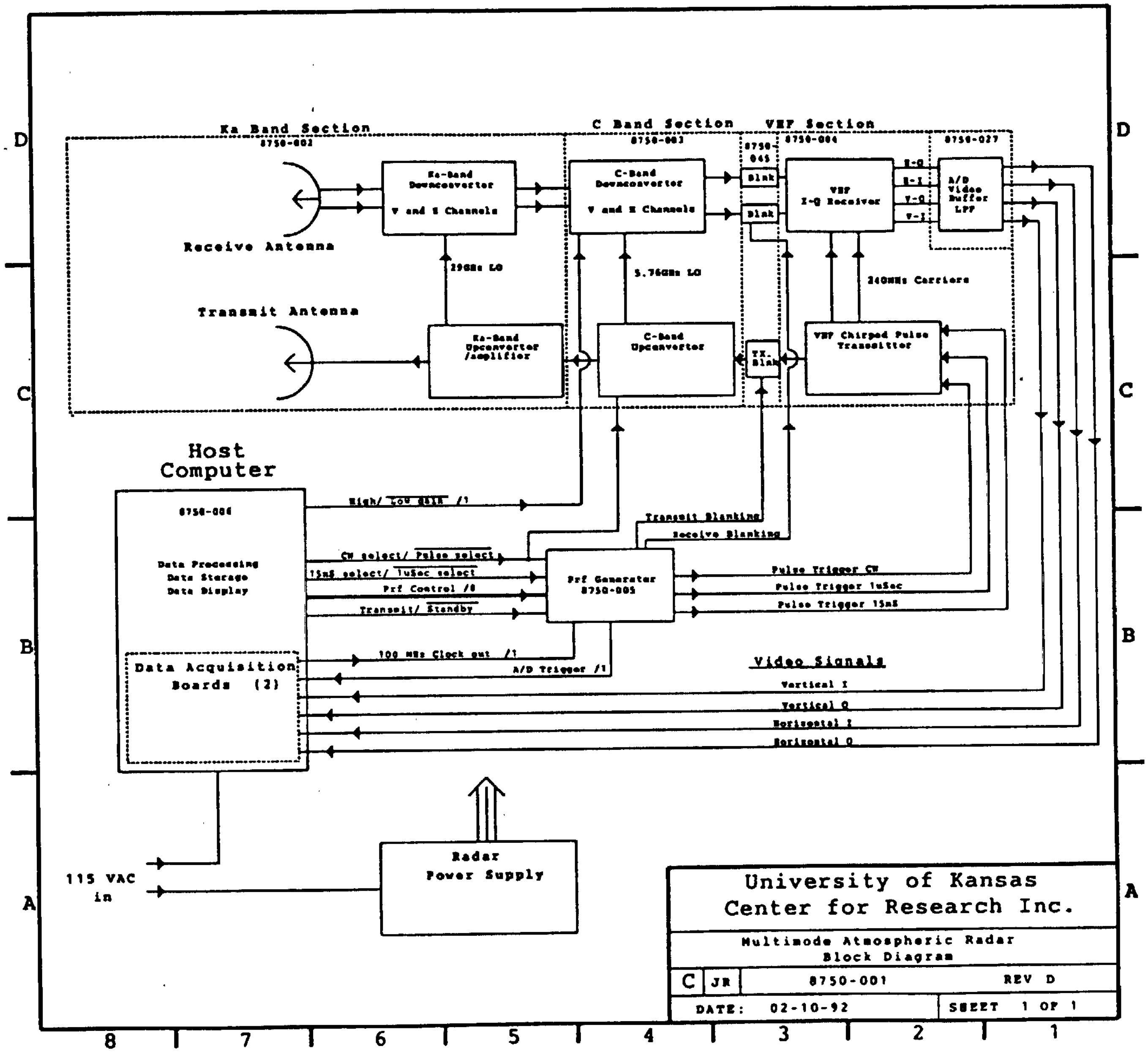

Figure 1. Pulse radar block diagram.

Figure 2 shows reflectivity measurements for a single range cell during a rain shower in October of 1991. Plotted along with the radar reflectivity is the magnitude of the radial velocity and data from a tipping-bucket-type rain gauge. This shower was associated with a rapidly moving cold front that passed from northwest to southeast through the area. The frontal passage is manifested in the data by a momentary drop in radial wind velocity at 20 minutes past the start of the shower. This drop is due to the change in wind direction from one air mass to the other.

FM-CW Mode

The third modulation type operational on the KU mm-wave atmospheric radar is FMCW. This mode provides high signal-to-noise ratio with low transmit power. Figure 3 shows the block diagram of the KU radar in FMCW mode. A highly linear frequency sweep is generated using a Direct Digital Synthesizer (DDS) module. The DDS module also produces one of four window functions used to reduce the sidelobes of the short-range feedthrough return. The synthesizer is configured and operated by a 68HC11 microcontroller operated in single chip mode. The 1.9-MHz bandwidth sweep is mixed with the 240-MHz continuous carrier provided by the pulse generation module. After filtering, weighting, and amplification, the resulting 260-MHz swept signal is passed through the same upconversion and TWTA sections as the pulse mode. On receive, the signal routing is the same as in the pulse mode except that a sample of the sweeping 260-MHz transmit signal serves as the LO in the I-Q receiver. Table 2 below summarizes the specifications of the radar in FMCW mode.

Table 2. Specifications of Radar in FM-CW Mode

Sweep Bandwidth	1.875 MHz
Sweep Period	2.18 ms
Range Resolution	80 meters
Doppler Velocity Capability	± 4 m/s

The entire radar is contained in four rack-mount cases, the PC controller, the VHF radar, the upconverter/downconverter, and finally, the Ka-band Traveling-Wave Tube Amplifier (TWTA). The antennas are mounted in a separate housing that bolts to the back of the radar rack. The rack is a shock-mounted container measuring 89cm x 69cm x 84cm. The external housing of the rack has clamshell lids that seal it against the weather. With the antennas removed and the lids in place, the radar can be shipped via normal freight carriers. Once in location, the radar can be operational within a few hours as no major assembly other than antenna connection is required. The weight of the system without antennas is 112 lbs. The radar uses 550W of prime power (115 VAC). Figure 4 shows the system mounted in a standard half-ton truck. Table 3 provides the general radar specifications.

We evaluated the radar's performance both from mobile and fixed platforms. Figures 5 and 6 show elevation scans of a small isolated shower in the vicinity of Lone Star Lake, a small lake about 6 miles southwest of Lawrence. The storm developed southwest of the lake and moved in a northeasterly direction toward the university. The first image shows a strong precipitation echo reaching to an altitude of 4 km at 10-km range. Other regions of enhanced reflectivity are

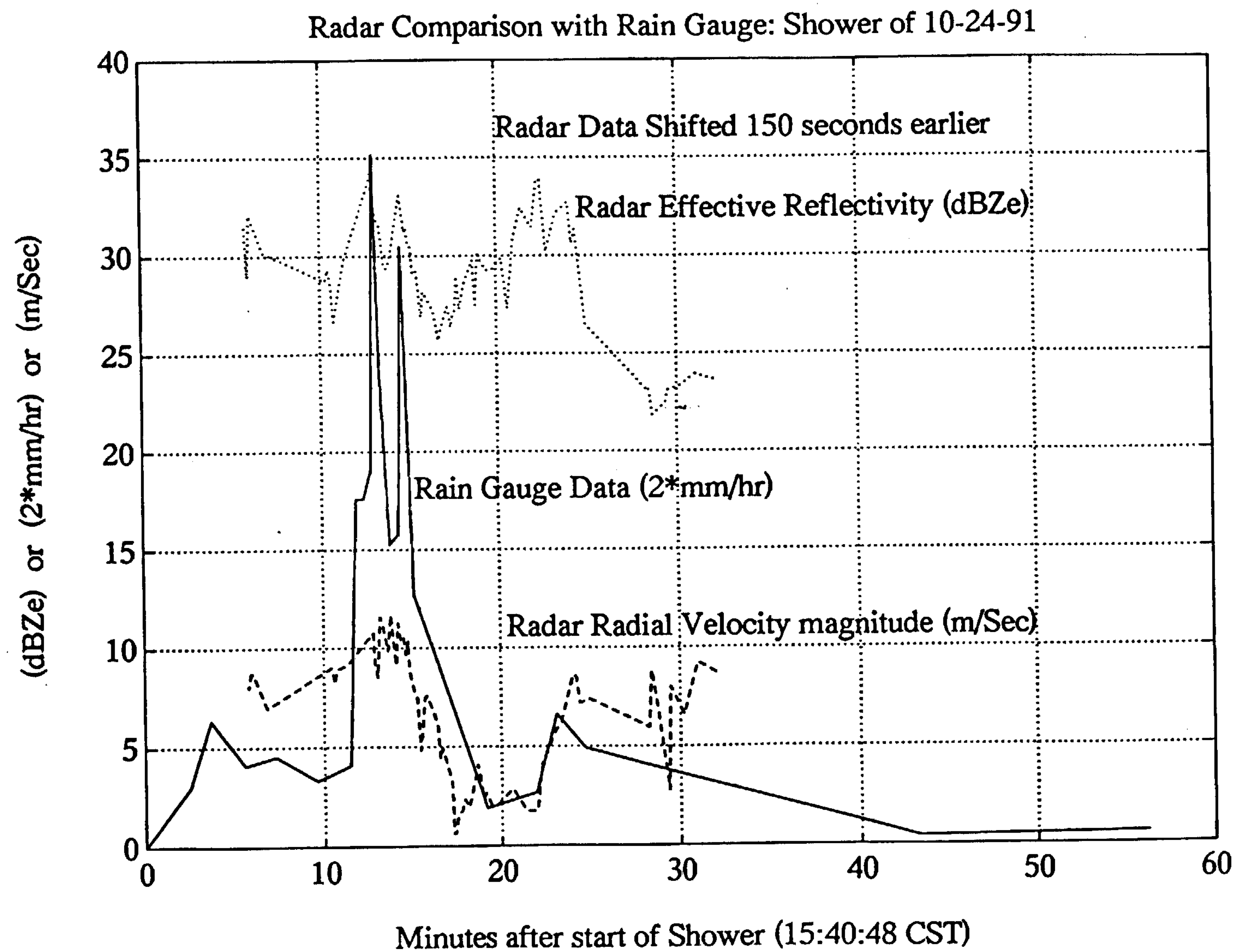

Figure 2. Pulse radar data.

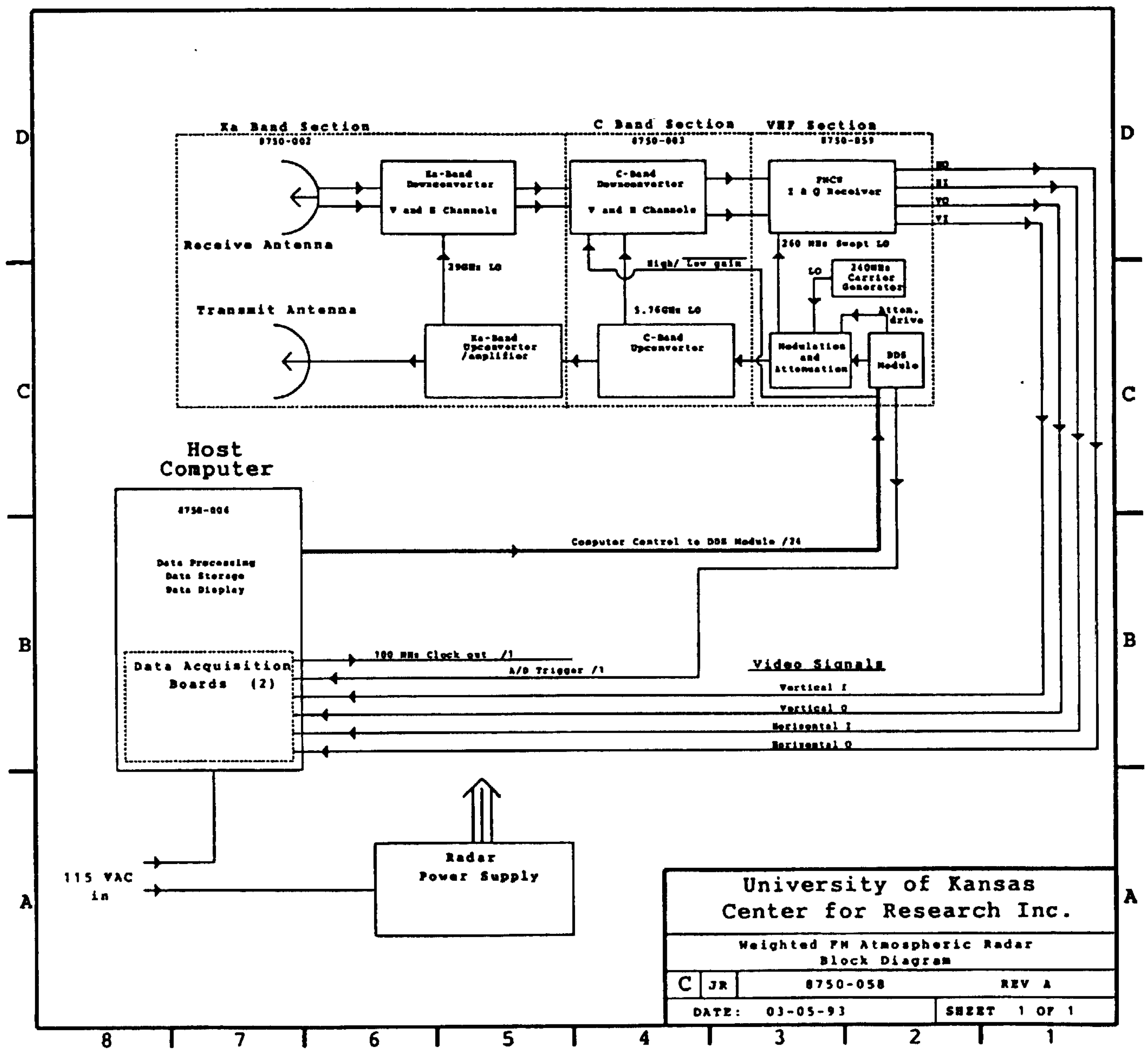

Figure 3. FM-CW radar block diagram.

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Figure 4. KU mm-wave radar mounted on truck.

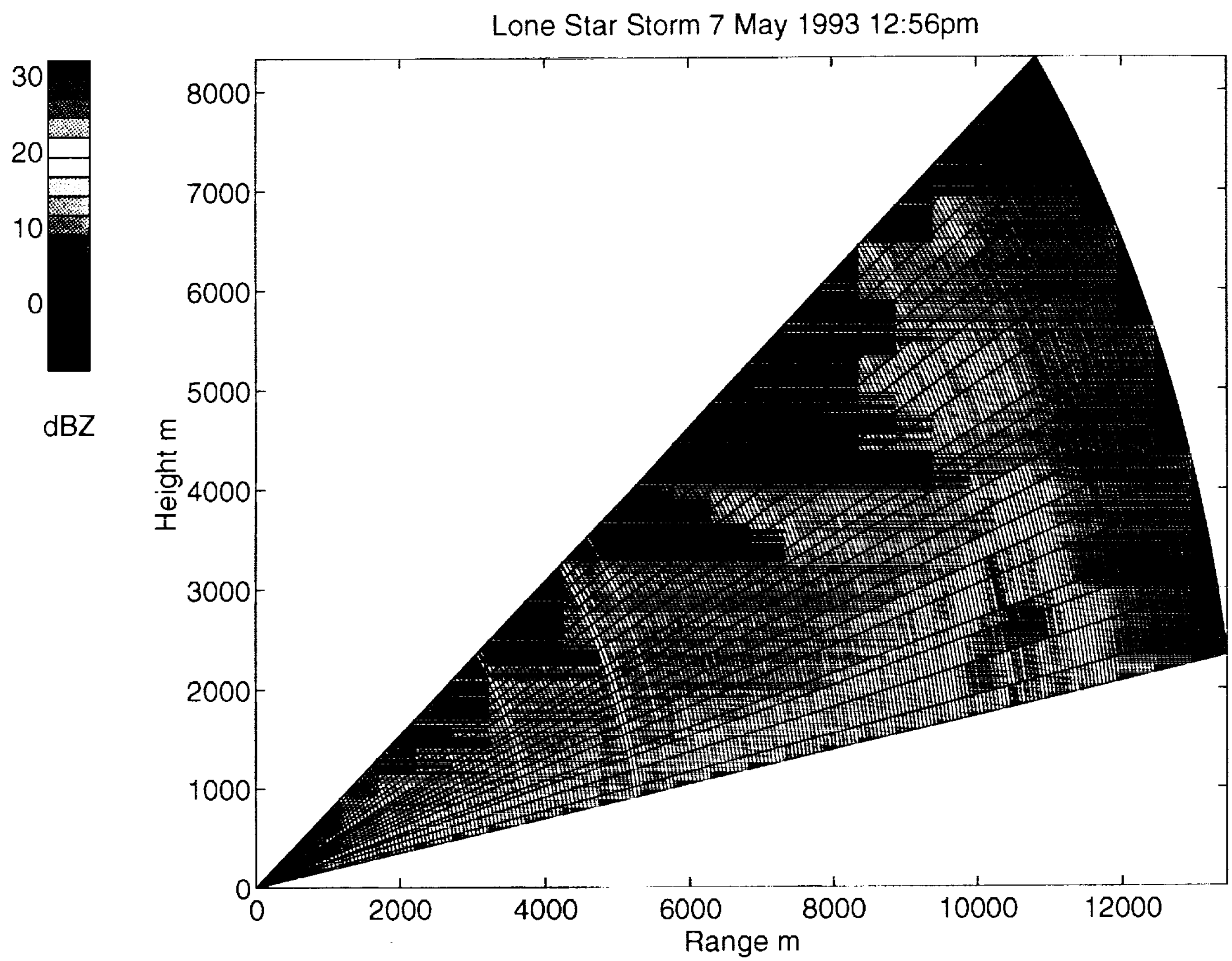

Figure 5. Elevation Scan of a Rain Shower

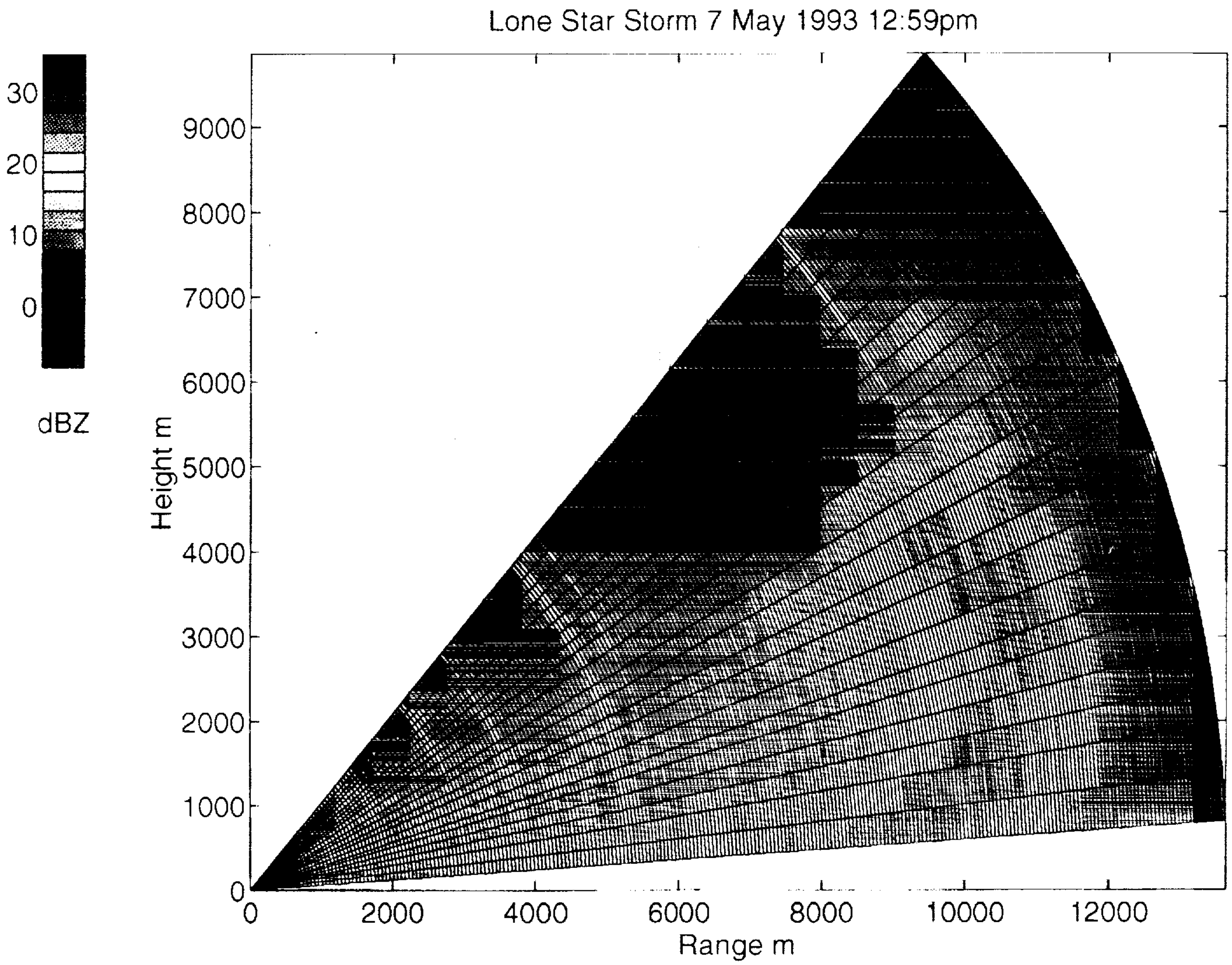

Figure 6. Elevation scan of a Rain shower

Table 3. General Radar Specifications

Center Frequency	35 GHz
Peak Output Power	14 Watts (CW TWTA)
Polarization	V transmit, V and H receive
Transmit Antenna	30.5 cm parabolic dish; 1.9° beamwidth
Receive Antenna	30.5 cm dual polarized lens-horn 2.1° beamwidth
Dimensions	132cm x 69cm x 84cm (with antennas in place)
Weight	112 kg
Power Consumption	550 W (of which 250 Watts is for the TWTA)
Range of Operation	10 m to 10 km
Mass Data Storage	20 MB replaceable

shown above the precipitation area and out in front of the storm at a range of 7 km and an altitude of 3.7 km. The second image, taken 3 minutes after the first, shows vertical development of the precipitation region reaching to 5 km and a curvature of the precipitation echo near the surface due to the horizontally diverging winds of the downdraft.

Modeling

The development of mm-wave sensors for the observation of these intermediate scale phenomena requires knowledge of their interaction with electromagnetic radiation. Although current understanding of mm-wave propagation through and backscatter from spherical liquid targets is fairly well advanced, the application of scattering theory to the complex shapes found in ice crystals is not. Some models have been developed for predicting scattering from atmospheric particulates in the microwave region. However, none of these models has been tested at millimeter wavelengths. There exists a need to apply these long wavelength models at the shorter wavelengths and test against measured data. Once this comparison is made, optimization of the old models or development of entirely new models will be necessary to develop accurate sensors in this region.

An effort is underway to model cloud particles using Finite-Difference Time-Domain (FDTD) techniques. Because the typical FDTD cell size is much larger than that of a typical cloud droplet, a "smart cell" approach is being developed that includes the near field of precipitation and cloud particles. An FDTD Matrix loaded with a distribution of these smart cells will be able to simulate numerically scattering from cloud and precipitation regions. Further enhancements to this technique could involve scatter from a distribution of ice needles and other shapes with varying degrees of correlated orientation.

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Related Presentations and Journal Publications

Ronnau, J. F., S. Haimov, and S.P. Gogineni, "The Effect of Signal-to-Noise Ratio on Phase Measurements with Polarimetric Radars," accepted for publication: Remote Sensing Reviews, August 1993.

Ronnau, J. F., and Gogineni, S. P., "A 35-GHz Multimode Radar for Atmospheric Sensing," at Specialty Meeting on Airborne Radars and Lidars, 7-10 July, 1992, Toulouse, France.